The volcanism-related multistage hydrothermal system of El Jaroso (SE Spain): Implications for the exploration of Mars

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The SE Mediterranean margin of Spain is an extremely interesting area of synchronous interaction of tectonic, volcanic, evaporitic and mineralizing hydrothermal processes. This works tackles the multiple relations among these processes by the study of a specific and representative case: the 'Jaroso Hydrothermal System'. The hydrothermal fluids were genetically linked with the late episodes of the Upper Miocene calc-alkaline and shoshonitic volcanism of the area. The ascent of the fluids was mainly controlled by the Palomares fault in Sierra Almagrera. In the shallow-marine basin of Las Herrerias, the movement of the acid solutions was controlled by both NNE-SSW and N150E normal faults and WNW-ESE wrench reverse faults. At least three mineralising stages were identified, although the particular formation of jarosite could be associated with both hypogenic and supergenic processes. We suggest that the multistage hydrothermal system of El Jaroso (Sierra Almagrera, Almería province, SE Spain), which is responsible for both the Jaroso ores (especially rich in jarosite) and the Las Herrerias sulfate-rich, shallow-marine laminites, could be exploited as a potential model with important implications for the exploration of Mars.
Key words: Jarosite, hydrothermal, shallow-marine, analog, Mars.

1. Introduction

A significant characteristic of the Neogene-Quaternary volcanic province of the SE Mediterranean Margin of Spain is its spatial and temporal relationship with hydrothermal mineralizations. They include oxy-hydroxides (e.g. hematite), gold, silver, Hg-Sb, and base-metal sulfides (Martinez-Frias *et al.*, 1989; Martinez-Frias, 1991, 1997). Hydrothermal sulfuric acid weathering of the ores has generated huge amounts of oxide and sulfate minerals of which jarosite is the most abundant.

The occurrence of sulfates on Mars has been expected since the Viking Landers found sulfur in the Martian soils in 1976, but the host mineral was never identified. If the amazing recent NASA's announcement about the discovery in Mars' Meridiani Planum region of jarosite is confirmed (MER, 2004), it would provide strong mineralogical evidence that liquid water once flowed through these rocks. Jarosite is an iron-bearing sulfate, which contains hydroxyl as a part of its structure $[(K,Na,X^{+1})Fe^{3+}(SO_4)_2(OH)_6]$, and which was first discovered on Earth in 1852 in Spain in the "Jaroso Ravine" (Fig. 1), which is the world type locality (Amar de la Torre, 1852). The "Jaroso Hydrothermal System (JHS)" is an extremely interesting late-volcanic episode, and the "Jaroso Ravine", located in Sierra Almagrera (Almeria province), is the best outcrop (approximately 2 km × 4.5 km) where the mineralization (Jaroso vein: 'Carmen', 'Animas' and 'San Cayetano' mines) and alteration, associated with the JHS, have attained the maximum surface expression.

Over the past twelve years, we have led several research projects dealing with the relations aming volcanism, tectonics and mineralization at this area, in cooperation with the Spanish Interministerial Science and Technology Commission, IUGS/UNESCO and NATO (Martinez-Frias, 1998, 1999). We propose here to revisit the peculiar characteristics of the volcanism-related multistage hydrothermal system of El Jaroso, as a potential terrestrial analog for the exploration of Mars and to gain knowledge from its geology, geodynamic controls, geochemistry and paragenetic sequence.

2. Volcanic and Tectonic Framework

In a very recent work (Duggen *et al.*, 2003) regarding the reconstruction of the geodynamic evolution of the westernmost Mediterranean margin, it is indicated that a marked shift in the geochemistry of mantle-derived volcanic rocks, reflecting a change from subduction-related to intraplate-type volcanism, occurred between 6.3 and 4.8 Myr ago. Having in mind this model, it is important to note that the magmas generated in the SE Mediterranean margin of Spain include the following rock series: calc-alkaline, K-rich calc-alkaline, shoshonitic, ultrapotassic and alkaline basaltic (Lopez Ruiz and Rodriguez Badiola, 1980). Radiometric dating indicates two episodes of magmatic activity (Bellon *et al.*, 1983). The first began in the Late-Burdigalian/Early-

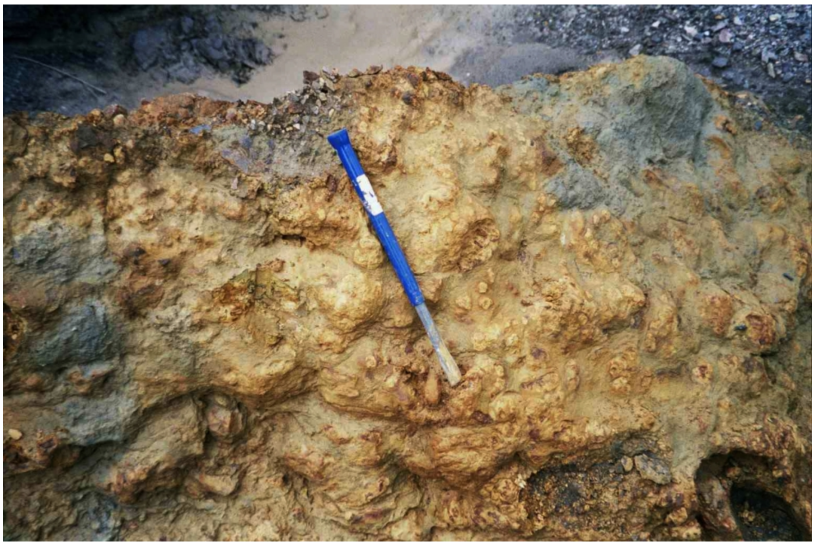

Fig. 1. Alteration crust rich in jarosite and other sulfates at El Jaroso Ravine, Sierra Almagrera (Almería, province, Spain).

Langhian with the generation of the calc-alkaline rocks, continued with the simultaneous extrusion of the calc-alkaline, K-rich calc-alkaline and shoshonitic rocks, and ended in the Messinian with the emplacement of the ultrapotassic rocks. The second episode began 2 Ma later, with the generation of the alkaline basalts. The K-rich calc-alkaline and shoshonitic rocks occur as domes, lacolites and dikes, and the main volcanic areas where they are found are: El Hoyazo and Vera (Almería province), and Mazarrón and Mar Menor (Murcia province).

Regarding the tectonics of this area (Sanz de Galdeano, 1990; Negredo *et al.*, 2002; Colomina *et al.*, 1998), it seems to be accepted that strike-slip and reverse fault systems have been active under the present day tectonic regime since the late Miocene. In general terms, NNE-SSW trending faults have been functioning as sinistral strike-slip faults, whereas E-W trending faults have been acting as reverse faults. The Carboneras and Palomares faults (the latter being one of the main structures which control the JHS) are two of the most noticeable sinistral NNE-SSW strike-slip faults of the regional tectonic system. As for the seismicity, the area has been subjected in historical times to destructive earthquakes (I > VIII, Medvedev, Sponheuer and Karnik (MSK) scale, Sponheuer and Karnik, 1964) and the instrumental seismicity indicates some earthquakes of a Richter magnitude higher than 4 (Instituto Geográfico Nacional, IGN, 1992).

More specifically, a Basin and Range-type model has been proposed for this sector of the Mediterranean margin (Lopez Gutierrez *et al.*, 1993) to explain the morphology of high zones (Sierras) and depressed zones (basin) as well as the structural relationships between the volcanic and mineralization processes. For instance, Las Herrerias trough inside the Vera-Garrucha Basin is controlled by both NNE-SSW and N150E normal faults and WNW-ESE reverse faults. Likewise, the model of fluid circulation proposed by Martinez-Frias *et al.* (1993) fits this structural scheme well. According to this model, the Sierras acted as recharge zones for meteoric waters while the discharge took place in the basin zones, where a mixture of meteoric, marine and magmatic waters occurred. The convective movements of the mineralising fluids would have been conducted by the Upper Miocene magmatic source of shoshonitic character which, as previously defined, is spatially and temporally associated with the mineralising hydrothermal system.

3. The Multistage Hydrothermal System of El Jaroso

In accordance with the "Basin and Range-type" model, the JHS affected both the Sierra Almagrera Triassic basement and the adjacent shallow-marine Miocene basin of Las Herrerias. Sierra Almagrera is a metamorphic massif with an NE-SW axis. It is composed of graphitic phyllites, quartz-rich phyllites and quartzites, with a paragenesis of quartz, muscovite, graphite and, to a lesser extent, biotite and garnet. Mineralization occurs as veins. Presently, there only remains visible on the surface some small ore veins which vary between 10–30 cm wide, although the famous 'Jaroso vein', of up to 10 m wide, was worked for more than 40 years (1839–1880). The vertical extent of the veins exceeds 400 m in many cases, displaying the following mineralogical zonation, from top to bottom (Martinez-Frias, 1991): (i) *Alteration zone (0–50 m)*: oxy-hydroxides (hematite, goethite), carbonates (calcite, siderite) and sulfates of Fe (*jarosite,* alunite) (Fig. 2), along with Cu, Pb and Zn; (ii) *sulfosalt-sulfides zone (50–300 m)*: bournonite, boulangerite, tetrahedrite, galena, sphalerite, chalcopyrite, pyrite, marcasite, barite, gypsum, siderite and traces of quartz; (iii) *zone of sulfides-sulfosalts (300–350 m)*: principally sphalerite, chalcopyrite, bournonite, barite and siderite (rare); and (iv) *sulfides zone (>350 m)*: principally pyrite and minor arsenopyrite, barite (very scarce) and quartz.

Minor pyrrhotite, nickeliferous pyrite, bravoite, veenite, gersdorffite, native bismuth and Bi-Ag-Pb sulfosalts have also been described (Morales, 1994).

The hydrothermal fluids also circulated through the sandy deposits which fill the basin and precipitated, mixed with the sediments, sulfate (mainly Ca and Ba sulfates), and silica rich laminites (Fig. 3). Tiny inclusions of KCl, Ti-

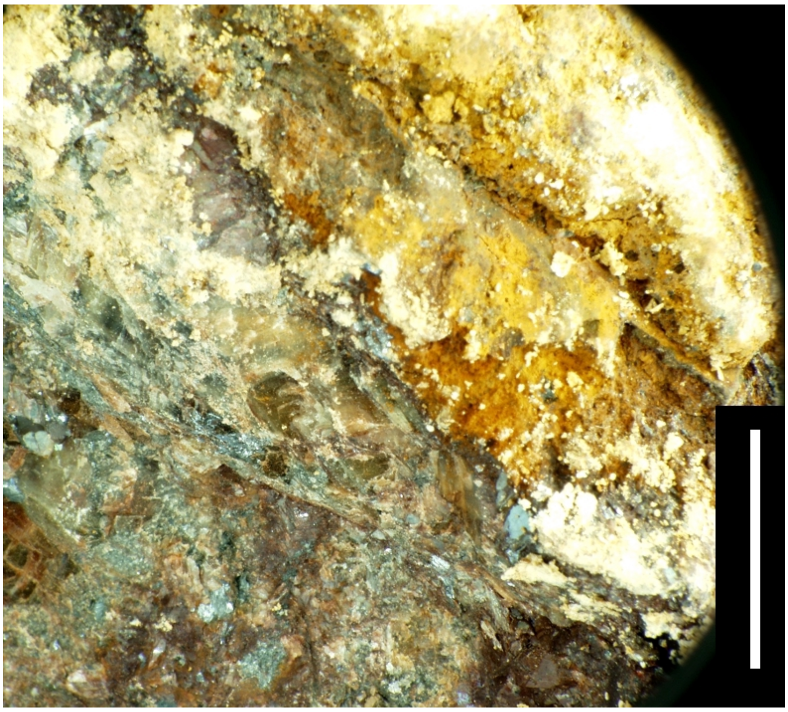

Fig. 2. Typical mineral associations at the Jaroso ravine (JHS), Sierra Almagrera representing various paragenetic stages. Yellow crust and patches: jarosite. Brown areas: Ca-Mg-Fe carbonates. White areas: barite. Bar scale: 2 cm.

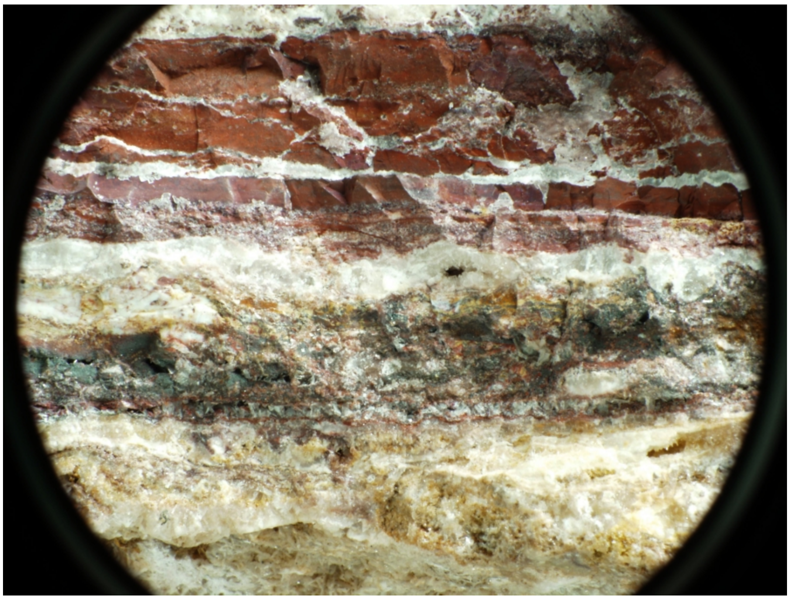

Fig. 3. Laminites from the shallow-marine basin of Las Herrerias. They are mainly composed of jasper, Ca, Ba and Fe sulfates and iron oxides and oxy-hydroxides. Circle diameter: 7 cm.

bearing hematite and sulfides (pyrite, sphalerite, galena, and cinnabar), and mineralized remains of marine microfossils (microforaminifera) are randomly disseminated within the laminites. Concerning the nature and temperature of the mineralizing solutions (Martinez-Frias, 1998), aqueous, two- and three-phase fluid inclusions were found having homogenization temperatures between 150 and 360°C. Three types of fluid inclusions were found: (i) two-phase (L + V) inclusions (TH = 330–360°C); (ii) aqueous, two-phase (L + V) inclusions with the additional presence of trapped solids (KCl and hematite) (TH = 270–350°C), and (iii) aqueous, two-phase (L + V) or three-phase (S + L + V) inclusions (TH = 160–260°C). Isotopic values of δ^{34}S in barites (Martinez-Frias, 1998) from Sierra Almagrera and Las Herrerias range between +23.3 and +23.6 (‰) V-SMOW, indicating the participation of marine waters in the JHS (δ^{34}S value ∼+23‰ for Upper Miocene marine sulfates, Burdett *et al.*, 1989)

4. Discussion

Very probably no place on Earth is truly like Mars. Nevertheless, it is possible to define potential sites on our planet where environmental conditions (geology, tectonics, mineralogy, hydrothermalism, etc.) approximate, in some specific ways, those possibly encountered on Mars at present or earlier in that planet's history. The likely predominance of basaltic crust on Mars suggests that hydrothermal fluids and associated deposits should be enriched in Fe, Mg, Si and Ca, with surficial deposits being dominated by lower temperature, mixed iron oxy-hydroxide, sulfate and carbonate mineralogies. We know that there has been extensive volcanic activity on Mars, and there is abundant evidence indicating that water has been present on and below the surface of Mars. The combination of volcanoes and liquid water on any planet leads inevitably to hydrothermal systems (Shock, 1997). Various authors (such as Jakosky, 1997; Farmer, 2000; Christensen *et al.*, 2000; Urquhart and Gulick, 2003, among others) have proposed that large-scale hydrothermal systems may have operated beneath the Martian surface at some time during the planet's history. More specifically, it had already been suggested that jarosite, hematite and/or ferrihydrite, maghemite and/or magnetite could be produced on Mars via hydrothermal processes (Bishop, 1999).

Considering the peculiar spatial and temporal coalescence of volcanism, tectonism, mineralizing hydrothermal episodes and intense evaporitic events (Mediterranean saline crisis) in SE Spain, some previous works had already suggested the significance of this Mediterranean area as a relevant geodynamic model to follow (Martinez-Frias *et al.*, 2000, 2001). The JHS, which is responsible for both the Jaroso ores (especially rich in jarosite), and the Las Herrerias sulfate-rich laminites could be exploited, as a volcanics-related model for early Mars. As appears to occur in Meridiani Planum, saline Cl-rich hydrothermal fluids, dominated by the precipitation of sulfates (mainly jarosite), were responsible for the formation and emplacement of the mineralization. The understanding of the peculiar volcanism-related multistage hydrothermal system of El Jaroso can aid to a) identify the possible sources of distribution of volatiles, especially water, within similar Martian systems, b) their evolution and c) the environmental conditions which could have played an important role for the prebiotic synthesis of organic compounds necessary for life's origin.

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